




The sspm R package: spatial surplus production models for the management of northern shrimp fisheries

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Statement of need

1. Population models, in particular fisheries productivity models, rarely integrate important spatially-structured ecosystem drivers
2. The Northern Shrimp stock in the Newfoundland and Labrador Shelves currently lacks a population model
3. Current SPM models are rarely spatially explicit and usually cannot account for relevant ecosystem drivers
4. Fisheries managers lack user-friendly, flexible tools to implement and apply SSPMs

Summary

Population modelling is an exercise of interest within environmental sciences and adjacent fields. Early population models such as the logistic model assumed that while the abundance of a population might change over time, the conditions governing parameters affecting that rate of change, such as the maximum rate of growth or the carrying capacity of the population, stay constant over time (Gotelli, 2008). Modern population models increasingly acknowledge the non-stationary nature of wild populations and work to incorporate environmental fluctuations into dynamic models (Thorson et al., 2017, 2015). Population models designed to answer applied resource management questions, such as fisheries stock models, increasingly address how the dynamics of stocks vary across space and time.

Resource managers are becoming increasingly interested in how variation in ecosystem factors such as predator abundance and abiotic variables impact the spatiotemporal variability of population parameters, such as productivity (Szuwalski & Hollowed, 2016; Zhang et al., 2021). Further, treating spatially structured stocks as single unstructured stocks can lead to substantially biased estimates of population change (Thorson et al., 2015). However, stock models that explicitly incorporate spatial dynamics and time-varying ecosystem variables are still rare in fisheries science, despite the push for more ecosystem-based management methods in fisheries management (Berkes, 2012; Crowder et al., 2008; Tam et al., 2017).

Surplus production models (SPMs) are one of the classic models used in fisheries and are based on modelling changes in the total biomass of a stock in a given location over time as a function of current stock abundance and fishing pressure (Walters et al., 2008). Classically, SPMs assume single unstructured stocks with purely logistic dynamics (Walters et al., 2008) and, as such, have been of limited use for modelling more complex stocks. They are useful in

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data-poor contexts where the age structure of the population is not accessible or when age or length structure do not change substantially over time (Prager, 1994; Punt, 2003).

Two limitations of classic SPMs is the assumption of spatially constant productivity, and that stock productivity is affected only by stock abundance and fishing. These assumptions ignore the effect of global changes that are affecting fisheries, such as climate change, that affect the growth rates of stocks independently of fishing pressure. The Northern Shrimp (*Pandalus borealis*) in the Newfoundland and Labrador Shelves, which has undergone several periods of large-scale biomass change in the last two decades, despite a relatively constant harvest regime, is a prime example of a population thought to be affected by environmental conditions (DFO, 2019). These populations currently lack a population model to understand the drivers of this change and to predict how fishing pressure and changing environmental conditions may affect future abundance. In the context of climate change and shifting ranges, fisheries productivity is likely to be a moving target (Karp et al., 2019), and managers need better methods that account for varying productivity (Szuwalski & Hollowed, 2016).

Population models like SPMs usually fall under the two following categories: process-based and statistical models. Process-based models often rely on differential or difference equations and are based on replicating the underlying processes (e.g., predation, recruitment, dispersal) driving population dynamics. Statistical models instead fit a regression model to time series of population abundances, abundance indices, or productivities, with some assumed error distribution for variation around predictions. This allows for estimation of parameter uncertainty and ranges of model predictions and for flexibly incorporating potential ecosystem drivers into models (Plagányi et al., 2014). Statistical models also allow for straight-forward estimation of spatial variation in population parameters such as maximum productivity or density dependence from data, in the absence of theory predicting how these parameters should vary. In this paper, we use a statistical approach to fitting SPMs using Generalized Additive Models (GAMS), estimated using the mgcv R package (Wood, 2017) as the backend. We apply this approach to the population of Northern Shrimp of the Newfoundland and Labrador Shelves, leveraging the smoothing properties of GAMs to account for varying productivity across time and space. The resulting model is a spatial SPM (SSPM), implemented via a R package *sspm*.

While the initial application of this model was modelling Newfoundland and Labrador Northern Shrimp stocks (Pedersen et al., 2022), The R package *sspm* is designed to make spatially-explicit surplus production models (SSPM) simpler to estimate and apply to any spatially structured stock. The package uses GAMs to estimate spatiotemporally varying biomass, and to estimate SSPMs based on changes in fitted biomass, observed catch, and spatially structured environmental predictors. It includes a range of features to manage biomass and harvest data. Those features are organized in a stepwise workflow, whose implementation is described in more detail in Figure 1.

1. Discretization and aggregation of spatially structured observations into discrete patches, with a range of methods of discretization (random or custom sampling, Voronoi tessellation or Delaunay triangulation).
2. Spatiotemporal smoothing of biomass and environmental predictors using GAMs.
3. Computation of surplus productivity based on biomass density and fishing effort.
4. Fitting of SSPMs to productivity data with GAMs.
5. Visualization of results, including confidence and prediction intervals.
6. One-step-ahead prediction of biomass for model validation and scenario-based forecasting.

Although it was developed in a fisheries context, the package is suitable to model spatially-structured population dynamics in general.

Package design

The package follows an object oriented design, making use of the S4 class systems. The different classes in the package work together to produce a stepwise workflow (Figure 1).

88 The key workflow steps are:

- 89 1. Delineation of the boundary of the region of interest for the model. Boundary data
90 is provided as a shapefile and converted into a `sspm_boundary` object with a call to
91 `spm_as_boundary()`.
- 92 2. The region within the boundary is discretized into patches with the `spm_discretize()`
93 function, creating a `sspm_discrete_boundary` object.
- 94 3. The `spm_as_dataset()` function turns user-provided data frames of raw observations
95 into `sspm_dataset` objects that explicitly track locations, data types, and aggregation
96 scales for each input. `sspm` recognizes three types of data: **trawl** (i.e. biomass estimates
97 from scientific surveys), **predictors**, and **catch** (i.e. harvest).
- 98 4. The `spm_smooth` function use spatiotemporal GAM models to smooth the biomass and
99 predictor data, based on the spatial structure from `sspm_discrete_boundary`. The user
100 specifies a GAM formula with custom smooth terms. The output is another `sspm_dataset`
101 object with a `smoothed_data` slot which contains the smoothed predictions for all patches.
- 102 5. The `spm_aggregate_catch` function aggregates catch into patches and years, and calcu-
103 lates patch-specific productivity for each year as the ratio of estimated biomass density
104 plus catch from the next year, divided by estimated biomass density of the current year.
105 The result is returned as a `sspm_dataset`.
- 106 6. The `sspm` function combines productivity and predictor datasets into a single dataset.
107 Additionally, the user may create lagged versions of predictors with `spm_lag()` and split
108 data into testing and training sets for model validation with `spm_split()` at this stage.
- 109 7. The `spm()` function is used to fit a SSPM model to the output of step 6, using a GAM
110 model with custom syntax able to model a range of SSPMs. The output is an `sspm`
111 object.
- 112 8. Predictions from the fitted model can be obtained using the built-in `predict()` method,
113 and plots with the `plot()` method.

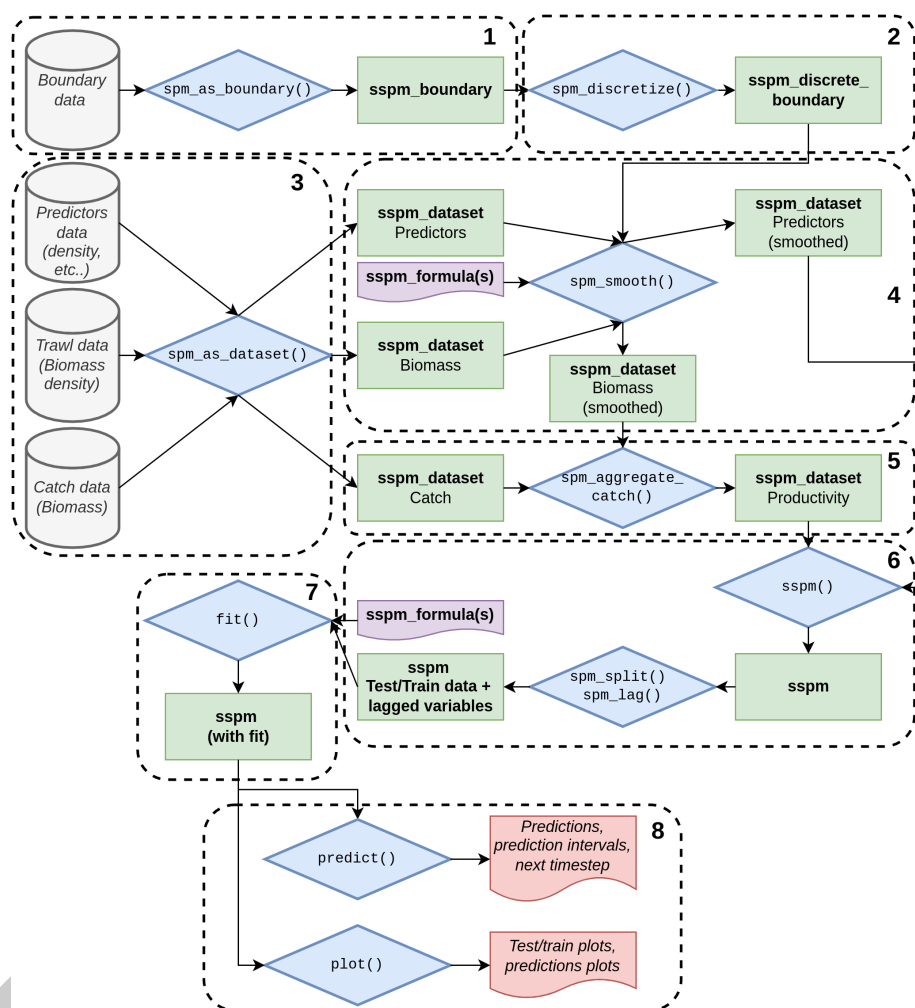


Figure 1: The sspm workflow.

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